ANALYSIS OF TRANSVERSE COMPRESSION AND IN-PLANE SHEAR IN UNIDIRECTIONAL COMPOSITES BY A PROGRESSIVE DAMAGE MODEL IN PRESENCE OF FIBER ROTATION

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Abstract

A continuum damage model for the prediction of the onset, evolution of intra-laminar failure mechanisms and the collapse of structures manufactured in fiber-reinforced plastic laminates was proposed by Maimi et al. based on LARC failure criteria. An extended model is proposed to incorporate finite fiber rotation in fiber reinforced plastic laminates during the continuous damage evolution using continuum mechanics. The model prediction will be assessed with a set of experiments in quasi-static conditions for rectangular, end-loaded, off-axis and transverse compression specimens conducted by Koerber et al. The simulation is carried out in different initial fiber orientation and the final failure strength of each case is calculated. Koerber experimental findings also include fiber rotation measurements which are used for evaluation of the model ability to predict fiber scissoring. Experiments report different failure mechanisms for different specimens that are observed using digital images of the damaged specimens. The proposed model is also capable of capturing the damage mechanisms. Therefore, digital images are compared to numerical results in order to emphasize the ability of the model to predict dominant failure modes.

1. Introduction

Composite materials application has been growing fast during the last decades. It has widen from more critical industries like aerospace to consumer product. The importance of simulating the mechanical behavior of composite structures is undeniable. Different phenomena are taking place during the loading process that the models including them will reveal better performance under complicated loading conditions. Elastic behavior, damage evolution and plastic deformation of the matrix are among those. One important phenomenon in the composites is the fiber rotation caused by loading that has got less attention by the research community. In this research an extended continuum damage model [1], [2] is used to simulate behavior of the unidirectional composites in presence of fiber rotation, also called fiber scissoring, and bi-linear shear plasticity.

2. Model

Maimi et al [3], [4], [5] developed an intra-laminar continuum damage model. The failure criteria used for this model is Larc [6], [7], [8] which is a well-established criteria for the composites. The model is extended by Eskandari et al. [1] to include fiber rotation during the elastic deformation and damage

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evolution. In order to calculate the fiber rotation in each step, the total rotation of the element, $\boldsymbol{R}_t$, is broken down to rigid rotation, $\boldsymbol{R}_r$, and fiber rotation, $\boldsymbol{R}$. The rigid rotation is calculated based on the rigid body kinematics as:

$$\dot{\boldsymbol{R}}_r = \boldsymbol{\Omega}\boldsymbol{R}_r, \tag{1}$$

where $\boldsymbol{\Omega}$ is symmetric part of velocity gradient. Total rotation is also determined by the polar decomposition of the deformation gradient, $\boldsymbol{F}$, as:

$$\boldsymbol{R}_t = \boldsymbol{F}\boldsymbol{U}^{-1}, \tag{2}$$

where $\boldsymbol{U}$ is stretch tensor. By having total rotation and rigid rotation, the fiber rotation reads:

$$\boldsymbol{R} = \boldsymbol{R}_t\boldsymbol{R}_r^T, \tag{3}$$

After calculation of the fiber rotation for each Gauss point at the current time step, it is incorporated in Maimi damage model, in which the damage parameters are calculated based on the real fiber orientation rather than its initial value as:

$$\begin{bmatrix} \sigma_1^X \\ \sigma_2^X \\ \sigma_3^X \\ \sigma_{12}^X \\ \sigma_{13}^X \\ \sigma_{23}^X \end{bmatrix} = \begin{bmatrix} R_{11} & 0 & 0 & R_{21} & R_{31} & 0 \\ 0 & R_{22} & 0 & R_{12} & 0 & R_{32} \\ 0 & 0 & R_{33} & 0 & R_{31} & R_{23} \\ 0 & R_{21} & 0 & R_{11} & 0 & R_{31} \\ 0 & 0 & R_{31} & 0 & R_{11} & R_{21} \\ 0 & 0 & R_{32} & 0 & R_{12} & R_{22} \end{bmatrix} \begin{bmatrix} \frac{Q_{11}}{1-d_1^x} & Q_{12} & Q_{13} & 0 & 0 & 0 \\ Q_{21} & \frac{Q_{22}}{1-d_2^x} & Q_{23} & 0 & 0 & 0 \\ Q_{31} & Q_{32} & \frac{Q_{33}}{1-d_3^x} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{Q_{44}}{1-d_4^x} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{Q_{55}}{1-d_5^x} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{Q_{66}}{1-d_6^x} \end{bmatrix}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} R_{11} & 0 & 0 & R_{12} & R_{13} & 0 \\ 0 & R_{22} & 0 & R_{21} & 0 & R_{23} \\ 0 & 0 & R_{33} & 0 & R_{31} & R_{32} \\ 0 & R_{12} & 0 & R_{11} & 0 & R_{13} \\ 0 & 0 & R_{13} & 0 & R_{11} & R_{12} \\ 0 & 0 & R_{23} & 0 & R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix}^{-1} \begin{bmatrix} \epsilon_1^X \\ \epsilon_2^X \\ \epsilon_3^X \\ \epsilon_{12}^X \\ \epsilon_{13}^X \\ \epsilon_{23}^X \end{bmatrix}, \tag{4}$$

In which, X represents material coordination and x shows spacial coordination. Based on the developed model a VUMAT subroutine is generated in ABAQUS [9] and the material properties of IM7-8552 are utilized in the simulation, using [10] according to Table 1 and 2.

3. Results

The developed model is executed for transverse compression and in-plane shear for unidirectional polymer composites. The geometry and configuration of the laminates are chosen from [11] in order to

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Table 1. IM7-8552 properties.

E_1 (GPa)	E_2(GPa)	G_{12} (GPa)	ν_{12}	X_T	X_C	Y_T	Y_C	S_L
291.714	9.08	5.29	0.32	2323.5	1200.1	62.3	199.8	92.3

Table 2. IM7-8552 fracture toughness ($\frac{KJ}{m^2}$).

G_1^+	G_1^-	G_2^+	G_2^-	G_6
81.5	106.3	0.28	1.31	0.79

compare the results. The analysis are implemented for different initial fiber orientations in quasi-static mode. The results for 15°, 30°, and 45° are illustrated in Figure 1. In these cases there is a good agreement between the numerical results and experimental tests. The model is able to capture the stiffening due to fiber rotation. Besides, the final failure is sensitive to the initial fiber orientation, as it decreases by increasing the angle. The final fiber rotation is also predicted with a good agreement by the experiments that is presented in Table 3.

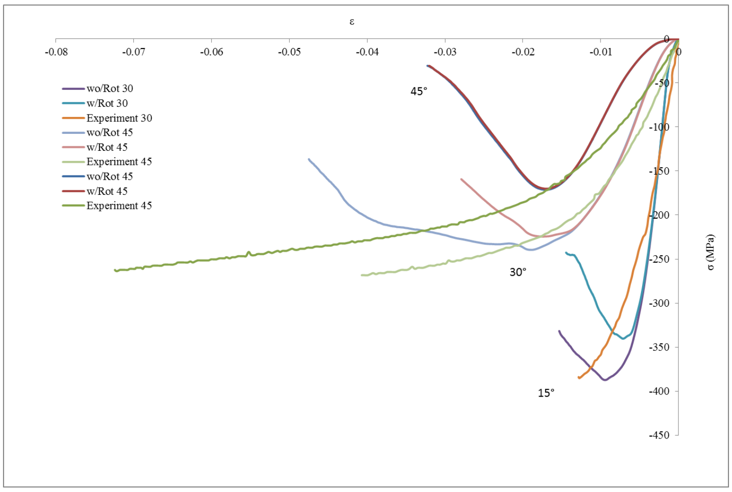

Figure 1. Stress-strain curves for 15°, 30°, and 45°.

On the other hand, the results for 60°, 75°, 90° are presented in 2 that reveals the failure stress are the same for different fiber orientation in this case. This results is sensible because by increasing the fiber angle, the matrix becomes dominant in the mode of failure. So by varying the fiber angle, the failure strength should not change. This is approved by experiments as well since there is negligible difference in strengths of these samples. Also both the numerical data and experiments showed zero fiber rotation in these cases so they have nothing to do with fiber scissoring phenomenon.

4. Conclusion

An extended continuum damage model is used to model compression and in-plane shear for unidirectional composites. The model reveals a good agreement with experiments in predicting fiber rotation. It can also predict final failure for cases with fiber orientation up to 45°. For higher fiber angles, there is negligible fiber rotation and due to plastic behavior of the matrix which is not fully developed in the

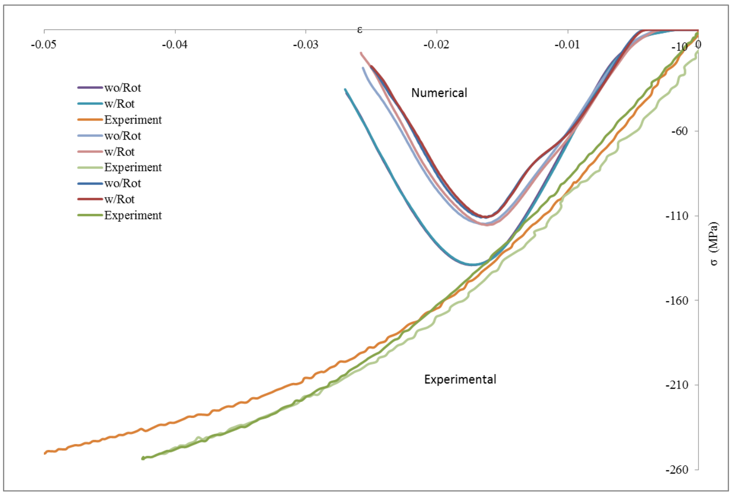

Figure 2. Stress-strain curves for 60°, 75°, and 90°.

Table 3. Final fiber rotation

Initial fiber orientation (°)	Experiment (°) [11]	Numerical (°)
15	1.9	1.67
30	2.3	2.05
45	1.3	1.1
60	≈ 0	0
75	≈ 0	0
90	≈ 0	0

model, accurate strengths cannot been predicted. Therefore, it is recommended to incorporate a robust plastic model for the matrix deformation in the current model.

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